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Minority Carrier Lifetime and Interfacial Recombination Velocity in GaAs/AlGaAs Double Heterostructures

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14. ABSTRACT

A novel technique is used to determine the minority carrier lifetimes, the interface recombination velocity, the internal radiative quantum efficiency, and the radiative recombination constant from PL decay measurements on a set of three samples and published theory. This technique is used to determine for the first time the minority carrier lifetimes of p-GaAs in double heterostructures that were grown by molecular beam epitaxy (MBE) at ARL. The results show the high quality of our bulk GaAs and the GaAs/AlGaAs interface in double heterostructure samples, and provide guidance for studies aimed at improving the quality of GaAs grown by MBE at the U.S. Army Research Laboratory (ARL).

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1. Introduction

Knowledge of minority carrier lifetimes is essential for the design and analysis of high-efficiency semiconductor solar cells (*1*) and other optoelectronic devices (*2*). Photoluminescence (PL) decay time measurements, which are typically used for the determination of the minority carrier lifetime in gallium arsenide (GaAs), are sensitive to surface recombination (*3, 4*), recombination at the active layer/substrate interface (*5*), and self-absorption of recombination radiation (*6, 7*). Due to the large surface recombination velocity (10^5–10^6 cm/s) at the free GaAs interface (*4, 8*) and the substrate/active layer interface (*5*), measurements of the PL decay time can be dominated by these effects depending on the carrier density, the sample thickness, and the bulk defect density in the GaAs sample. Consequently, the unambiguous determination of minority carrier lifetime typically requires measurement over a range of sample thicknesses and carrier densities. The surface and interface recombination velocity in GaAs was considerably reduced by the use of p-type GaAs/aluminum gallium arsenside (AlGaAs) double heterostructures that confine minority carriers in the GaAs quantum, well-defined by the potential barrier at the GaAs/AlGaAs interface due to the larger bandgap in AlGaAs (*9*). Theoretical analysis showed that self-absorption of spontaneously emitted photons has significant effects on the lifetime of injected carriers in GaAs/AlGaAs double heterostructures (*7*). Minority carrier lifetimes and the radiative recombination constant were determined from PL decay time and internal radiative quantum efficiency measurements on GaAs samples, which were grown by liquid-phase epitaxy (LPE), and theory, which takes into account self-absorption and interface recombination (*10*). In this report we show that the minority carrier lifetimes, the interface recombination velocity, the internal radiative quantum efficiency, and the radiative recombination constant can be determined from PL decay measurements on a set of three samples and the theory developed by Nelson and Sobers (*10*). This technique is used to determine for the first time the minority carrier lifetimes of p-GaAs double heterostructures that were grown by molecular beam epitaxy (MBE) at the U.S. Army Research Laboratory (ARL).

2. Theory

In order to facilitate the discussion of the experimental results, we outline the essential features of Nelson and Sobers' theory (*10*). Including self-absorption and surface recombination, the effective minority carrier lifetime τ, is given by

$$\frac{1}{\tau} = \frac{1}{\tau_r} - \frac{F}{\tau_r} + \frac{1}{\tau_{nr}} + \frac{2S}{d}$$

$$= \frac{1}{\phi\tau_r} + \frac{1}{\tau_{nr}} + \frac{2S}{d}, \tag{1}$$

where τ_r is the minority carrier radiative recombination lifetime, F is the fraction of photons from radiative recombination that are self-absorbed, $\phi = 1/(1\text{-}F)$, τ_{nr} is the nonradiative recombination lifetime, S is the interfacial recombination velocity, and d is the sample thickness. For injected minority carrier densities that are small compared to the carrier concentration p_0 (for p-GaAs), $\tau_r = 1/(Bp_0)$, where B is the radiative recombination constant (*11*). Note that in samples with no AlGaAs barrier at the GaAs/substrate interface, the factor 2S in equation 1 is replaced by the factor $(S+S_i)$, where S_i is the recombination velocity at the GaAs/substrate interface. The factor ϕ in equation 1, which has been calculated for the GaAs/AlGaAs heterostructures (*7, 10*), depends on the sample's carrier concentration and thickness. ϕ increases as d becomes large compared to the absorption length of luminescence. For sufficiently large d, equation 1 shows that τ is limited by τ_{nr} and interfacial recombination.

3. Experimental Technique and Data

The recombination parameters, τ_r, τ_{nr}, and S, can be determined from equation 1 using measurements of the effective minority carrier lifetimes on three GaAs/AlGaAs double heterostructures with different GaAs thicknesses and the calculated (*7, 9*) values for ϕ. Calculated values of the parameter ϕ as a function of d for $p_0 = 2.6 \times 10^{16}$ cm^{-3} and for $p_0 = 1.2 \times 10^{18}$ cm^{-3} have been published in references 10 and 7, respectively. The GaAs/AlGaAs double heterostructures used in the carrier lifetime measurements consist of the following layers: a semi-insulating GaAs substrate, 500 Å p-Al$_.5$Ga$_.5$As, the p-GaAs active region, 500 Å p-Al$_.5$Ga$_.5$As, and a 50 Å p-GaAs cap layer. The carrier concentration is the same in the GaAs and the AlGaAs regions. Carrier thickness and concentration were determined by MBE calibration procedures and electro-chemical capacitance-voltage measurements on calibration samples. The carrier density and thicknesses of the samples are given in table 1.

Table 1. Sample data and PL decay times.

Wafer	p_0 (cm^{-3})	d (μm)	ϕ	τ (ns)
M1165	3×10^{16}	2.0	4.83	131
M1167	3×10^{16}	0.6	2.07	82
M1166	3×10^{16}	0.3	1.54	61
M1168	2×10^{17}	2.0		31

Carrier lifetimes in the GaAs/AlGaAs samples were measured using time-resolved photoluminescence (TRPL) at 300 K to obtain the PL decay time, which is the effective minority

carrier lifetime. Samples were excited using a 250-kHz repetition rate, ultrafast 632-nm laser (~1.5 mm beam diameter) that was derived from frequency-doubling the output of a regenerative amplifier-pumped optical parametric amplifier. Excitation laser power was varied over the range 0.27–29.9 mW, resulting in the initial excess carrier densities in the excited samples ranging between 6×10^{13} cm^{-3} and 7×10^{15} cm^{-3}. Photoluminescence was detected through a 700-nm long-pass filter, to minimize the laser scattering signal, with a fast 300-µm diameter Si photodiode. Data were acquired on a PCI averager card. The system response was measured to be ~2 ns.

Figure 1 shows the observed TRPL data for a sample, with d = 2 µm and $p_0 = 3 \times 10^{16}$ cm^{-3} for several excitation intensities. The PL decay is observed to be a single-mode exponential over roughly two decades with τ = 131 ns for excitation power ≤3.18 mW. For excitation power ≤3.18 mW, the estimated initial photoexcited carrier density is $\leq 6 \times 10^{14}$ cm^{-3}, indicating that the excited samples are in the weak-injection regime. Figure 1 shows that the PL decay cannot be fitted by a single-mode exponential for excitation power ≥12.4 mW, where the initial photoexcited carrier density is $\geq 3 \times 10^{15}$ cm^{-3} and the excited samples are entering the intermediate-injection regime. TRPL data for samples with $p_0 = 3 \times 10^{16}$ cm^{-3} and d = 0.6 µm and 0.3 µm, shown in figures 2 and 3, respectively, exhibit single-mode exponential decay over roughly two decades with τ = 82 ns and τ = 61 ns, respectively, for excitation power ≤1.13 mW. The observed PL decay time decreases to 31 ns for a sample with a 2 µm GaAs layer and $p_0 = 2 \times 10^{17}$ cm^{-3}, as shown in figure 4. The observed structure in the PL intensity at times greater than 250 ns is more pronounced as τ decreases, suggesting that it is an experimental artifact that is related to the detector/circuit frequency response. The sample characteristics, calculated values for ϕ, and the effective minority carrier lifetimes are summarized in table 1.
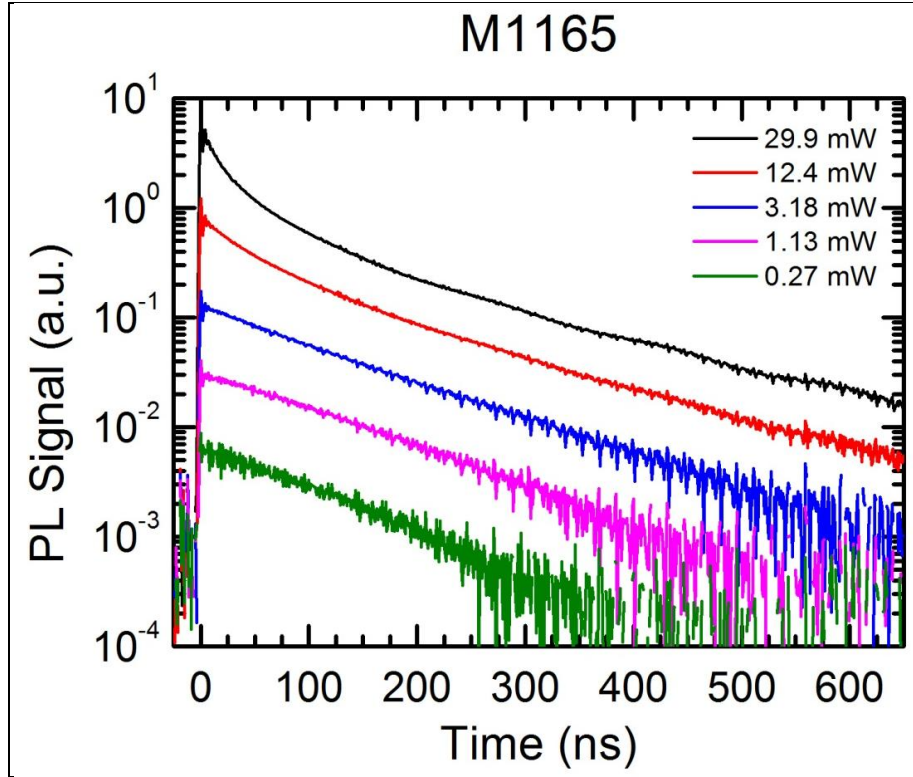
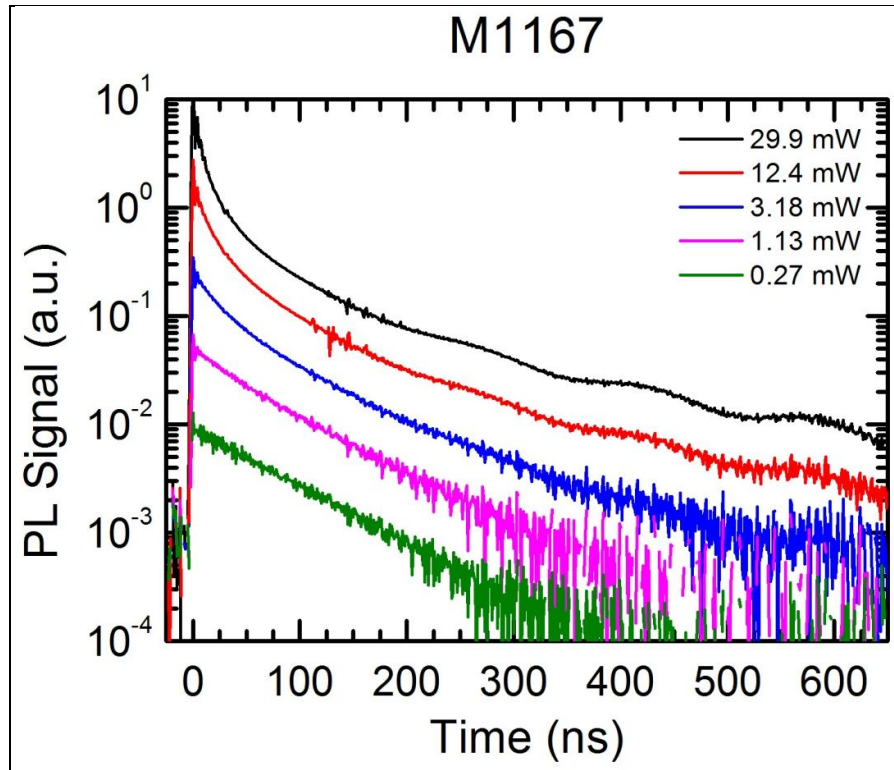Figure 1. TRPL of sample with a 2 µm GaAs layer and $p_0 = 3 \times 1016$ cm^{-3}.

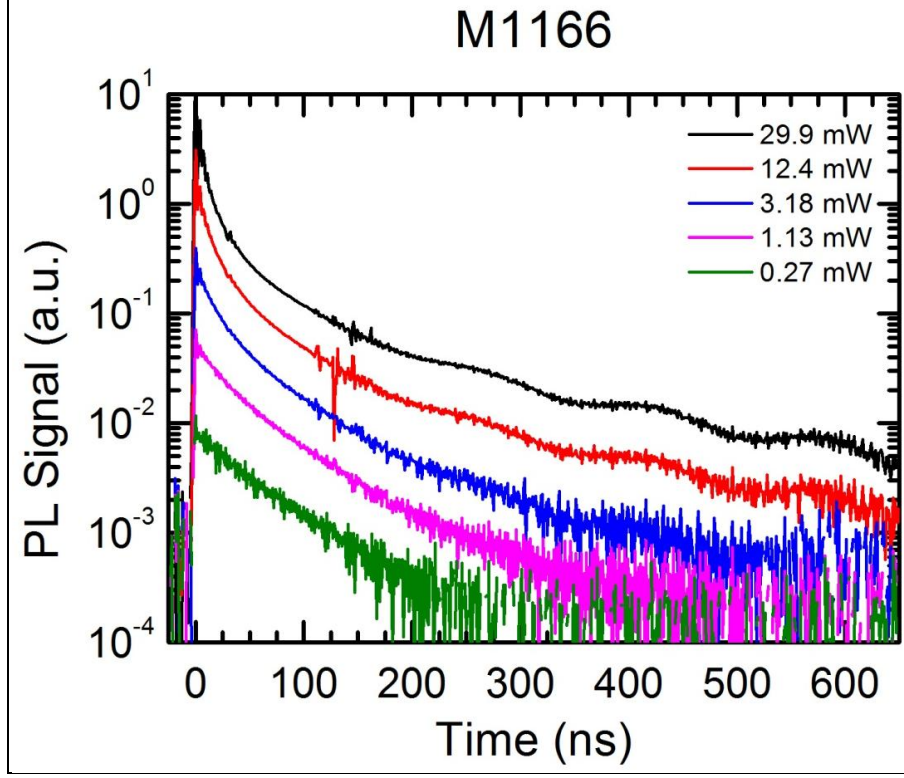Figure 2. TRPL of sample with a 0.6 µm GaAs layer and $p_0 = 3 \times 1016$ cm^{-3}.

4

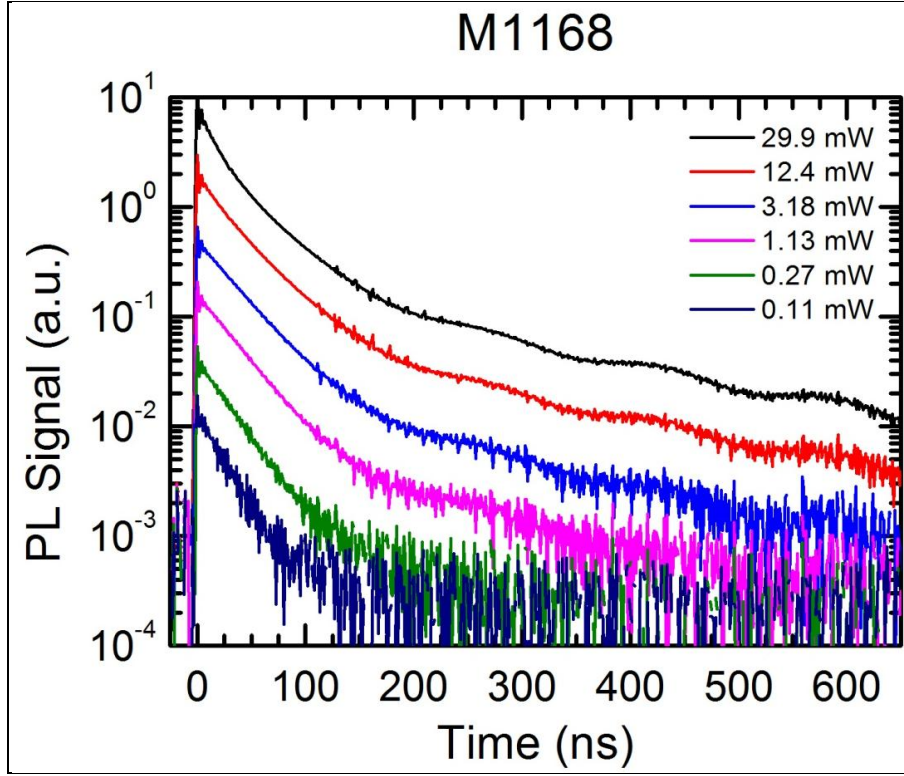Figure 3. TRPL of sample with a 0.3 μm GaAs layer and $p_0 = 3 \times 1016$ cm^{-3}.

Figure 4. TRPL of sample with a 2 μm GaAs layer and $p_0 = 2 \times 10^{17}$ cm^{-3}.

4. Data Analysis

The values for τ, d, and ϕ for the first three samples in table 1 are substituted into equation 1 to obtain three simultaneous equations, which are then solved to determine τ_r, τ_{nr}, and S.

The results obtained from the analysis show that for GaAs with carrier concentration of 3×10^{16} cm^{-3}, $\tau_r = 97.9$ ns, $\tau_{nr} = 208.9$ ns, S = 74.8 cm/s, and the internal radiative quantum efficiency $\eta = \tau_{nr}/(\tau_r + \tau_{nr}) = 0.68$. The low value of S obtained in our samples is comparable to the best values reported for MBE GaAs (*12*). We also determine that the radiative recombination constant, B = $1/\tau_r p_0 = 3.4 \times 10^{-10}$ cm^3/s, which is consistent with previous results (*10, 13*). Published results (*7, 10*) show $\eta > 0.90$ for the highest-quality GaAs, indicating that the τ_{nr} of our GaAs can be increased.

5. Conclusion

In this report we show that the minority carrier lifetimes, the interface recombination velocity, the internal radiative quantum efficiency, and the radiative recombination constant can be determined from PL decay measurements on a set of three samples and the theory developed by Nelson and Sobers (*10*). This technique is used to determine for the first time the minority carrier lifetimes of p-GaAs heterostructures that were grown by MBE at ARL. The results show the high quality of our bulk GaAs and the GaAs/AlGaAs interface in double heterostructure samples.

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List of Symbols, Abbreviations, and Acronyms

AlGaAs   aluminum gallium arsenide

ARL   U.S. Army Research Laboratory

GaAs   gallium arsenide

LPE   liquid-phase epitaxy

MBE   molecular beam epitaxy

PL   photoluminescence

TRPL   time resolved photoluminescence

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